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Comparison of FDMA and CDMA for Second Generation Land-Mobile Satellite Communications

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Abstract

CDMA and FDMA (both analog and digital) systems capacities are compared on the basis of identical link availabilities and physical propagation models. Parameters are optimized for a bandwidth-limited, multi-beam environment. For CDMA, the benefits of voice activated carriers, antenna discrimination, polarization reuse, return link power control and multipath suppression are included in the analysis. For FDMA, the advantages of bandwidth efficient modulation/coding combinations, voice activated carriers, polarization reuse, beam placement, and frequency staggering have been taken into account.

1. Introduction

In the long term, the land-mobile satellite channel will become bandwidth limited; hence it is important from the outset to identify and plan the introduction of techniques and technology offering maximum overall spectral efficiency. For this purpose, we have studied the CDMA and FDMA system capacities for a bandwidth-limited second generation land-mobile satellite communications system.

This paper presents a capacity analysis and comparison of CDMA and FDMA approaches as applicable to the voice service. Both digital and amplitude companded single sideband (ACSSB) analog modulations have been considered with FDMA. Analysis is conservative to ensure stated performance can be achieved, notwithstanding implemention uncertainties, using today's technology.

The organization of the paper is as follows. Section 2 states an objective basis for comparison and discusses the relevant system parameters. Section 3 presents the capacity analysis for each candidate system. Section 4 compares the performance of the candidate techniques. Potential capacity enhancement techniques are discussed in Section 5, and conclusions are drawn in Section 6.

2. System Parameters

The systems are compared on the basis of identical [1]

- $C/N_oW_s=$ total received signal to noise power ratio (L-band forward or return link),
- $\theta_{3\mathrm{dB}}$ = 3 dB satellite beamwidth,
- spatial coverage area (relative to $\theta_{3\mathrm{dB}}$).

All candidates are assumed to operate in a circuit switched demand assignment mode, with primarily voice traffic. Access control and signalling overhead has been neglected as a differentiating factor in comparing b/s/Hz of usable capacity versus C/N_oW_s. All beams are assumed to generate and terminate the same number of erlangs of traffic. The implications of non-uniform traffic is discussed in [3].

The issue of voice coding rate is avoided by expressing capacity in b/s/Hz rather than as a number of channels/kHz. ACSSB at a specific C/N_o value is treated as a 4.8 kb/s circuit to allow comparison on the basis of b/s/Hz.

The other system parameters and the assumptions made are as follows.

Antenna Pattern

The assumed spacecraft antenna illumination pattern was that of a parabolic reflector with constant illumination, and is given by

$$G(u) = 2(J_1(u)/u)^2 \tag{1}$$

where

$$u = \pi D \frac{\sin\theta}{\lambda}. \tag{2}$$

In (1) and (2), $J_1(\,)$ is the Bessel function of the first kind and first order, D is the antenna diameter, λ is the carrier wavelength, and θ is the off-axis angle.

Sensitivity to illumination pattern is not significant to the conclusions stated herein [3].

Multi-Beam Geometry

A hexagonal coverage contour with two apposite sides elongated was considered, as shown in Fig. 1. This contour is illuminated by 10 beams touching at -3 dB or 13 beams touching at -2 dB contours. The minimum antenna discrimination values indicate that FDMA capacity is optimized using 10 beams with 3 frequency bands. In Fig. 1, the notation $1^{s,r}$ refers to frequency band 1, right hand polarization with frequency staggering. Similarly 2^{l} denotes frequency band 2, left hand polarization, no staggering.

For CDMA, channelization by utilizing different frequency bands in different beams, in general, was not found to provide any significant capacity increase. However, using 13 beams touching at -2 dB contours provides higher capacity than 10 beams touching at -3 dB contours. Therefore, 13 beams with a single frequency band was used in the capacity analysis.

Frequency Staggering

Frequency staggering refers to offsetting the FDMA system frequency plans in different beams by one-half channel. For both digital and ACSSB FDMA, the interference reduction achieved by frequency staggering has been included in the analysis.

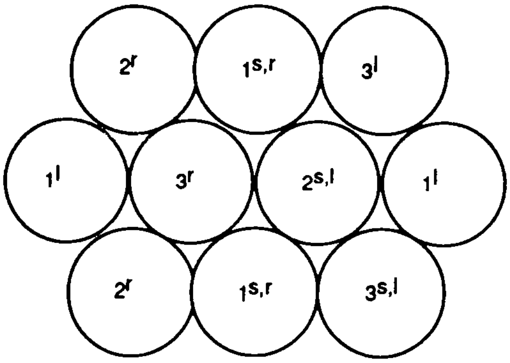

Figure 1: **10-Beam dual polarization configuration with a frequency reuse factor of 10/3.**

Power Control

Applying power control to compensate for the static losses incurred by signals travelling to and from the mobiles is a technique which can reduce interference in some cases. For the FDMA schemes, the effectivenes of power control on the worst case interference condition was found to be minimal, hence was not included in the analysis. Considering also implementation issues, power control was assumed to be applied to the return link of CDMA, but not the forward link.

Dual Polarization

Dual polarization was assumed for CDMA and digital FDMA, but not for ACSSB FDMA.

Grade of Service

The link analysis of a mobile satellite system involves a number of parameters which are subject to statistical variations. We have accounted for long-term and gross spatial variations (e.g., received power differences between the centre and edge of a beam) by assuming nominal worst-case values for such parameters. Small spatial and short-term variations were accounted for by applying a grade of service (GOS) approach.

A primary contributor to short-term variations is shadowing attenuation. We modelled shadowing as a two-state variable. Based on empirical data [2], the channel was assumed to be in the ON-state (i.e., errors are due to

AWGN and multipath but not shadowing) for 90% of the time. Thus, for system grades of service of 90% or less, defined at the voice decoder input, no particular effort to counteract shadowing need be applied. However, GOSs above 90% can be achieved by a power margin and/or interleaving. In this paper we consider a GOS of 90%.

3. Capacity Analysis[1]

3.1 CDMA

The capacity of a CDMA system, η, in units of b/s/Hz is given by

$$\eta = \frac{MR_b}{W_s} = \frac{C}{N_oW_s} \frac{(\frac{N_o'}{E_b})_{\mathrm{req}} \frac{1}{W_n}}{V(L_s + \alpha\rho(\frac{C}{N_oW_S}))} \quad (3)$$

where
M: total number of users in the system,
R_b: information bit rate per user,
W_s: total available bandwidth,
V: voice activity factor,
N_o: thermal noise spectral density,
$(E_b/N_o')_{\mathrm{req}}$: energy per bit to total noise density ratio required for a specific BER,
W_n: ratio of total bandwidth to the chip rate,
L_s: shadowing loss factor,
α: antenna discrimination factor,
ρ: polarization discrimination factor.

The parameters in (3) which are common to forward and return links are calculated as follows.

Coherent BPSK theoretically requires an E_b/N_o' of 6.8 dB to achieve a BER of 10^{-3}. For this we assumed the use of a rate 1/3, constraint length 6 convolutional code for which at a BER of 10^{-3} the coding gain is approximately 4 dB. Assuming an implementation margin of 2 dB, $(E_b/N_o')_{\mathrm{req}}$ was found as 4.8 dB.

The voice activity factor, V, was assumed to be 0.4.

The bandwidth to chip rate ratio, W_n, which depends on the filtering used, was assumed to be 1.125.

[1]Due to space limitations, the interested reader is referred to [3-5] for the derivation of the following equations.

Assuming that half of the users will transmit and receive left-hand circular polarization and the other half will use right-hand circular polarization, the polarization discrimination factor is

$$\rho = \frac{1}{2}(1 + x_{\mathrm{pol}}) \quad (4)$$

where x_{pol} is the cross polarization rejection factor. For a x_{pol} of 0.1, the polarization discrimination factor is $\rho = 0.55$.

The differences between the forward and return link capacity equations mainly lie in the antenna discrimination factors and shadowing loss factors.

In the forward direction, a mobile terminal will receive all the co-channel interference from the other users in its particular beam, plus some additional co-channel interference from all the other beams in the system at a reduced power level. For the beam geometry and the antenna radiation pattern assumed above, the forward link antenna discrimination factor was calculated as $\alpha_f = 0.255$ [3].

In the return direction, a particular beam of the satellite collects co-channel interference from all the users, weighted by the antenna gain in the direction of the co-channel users. The return link antenna discrimination factor corresponding to this situation was calculated as $\alpha_r = 0.169$. Note that these α_f and α_r values are for worst case user locations.

In CDMA, because it has a better antenna discrimination factor and shadowing loss factor, the capacity of the return link was found to be higher than the forward link capacity.

3.2 Digital FDMA

The capacity of a digital FDMA system is given by:

$$\eta = \frac{MR_b}{W_s} = \frac{C}{N_oW_s} \frac{1}{E_b/N_o'} \frac{1}{V} (1 - \frac{E_b}{N_o'} Y_o) \quad (5)$$

where N_o' is the total noise power density falling within the bandwidth of the receiver and is given by

$$N_o' = N_o + Y_oE_b. \quad (6)$$

In (6), Y_o lumps together the co-polar interference, cross-polar interference, and adjacent channel interference (ACI), i.e.,

$$Y_o = (I_{o-co} + I_{o-x} + I_{o-ACI})/E_b \quad (7)$$

where

I_{o-co}: co-polar interference spectral density,
I_{o-x}: cross-polar interference spectral density,
I_{o-ACI}: adjacent channel interference spectral density.

In FDMA, where the number of interferers is small, treating interference as Gaussian noise and adding it to the thermal noise on a power basis is a conservative approach. However, since the target bit error rate, 10^{-3}, is not very low, this approach is acceptable.

For the assumed beam geometry and antenna pattern, and using dual polarization, the forward and return link (E_b/I_{o-co}) values were calculated as 18.1 dB and 17.1 dB respectively. Similarly the forward and return link (E_b/I_{o-x}) values were calculated as 21.5 dB and 20.5 dB respectively. Intra-system interference densities are related to E_b, because increasing the total transmitted energy proportionally increases the interference. There is little difference between forward and return link capacities at the same C/N_oW_s value.

The upper limit of η is determined by the modulation technique, FEC code rate and frequency reuse factor. For example, a rate r coded PSK signal with q phases has a maximum bandwidth efficiency of

$$\eta = \beta r \, \frac{\log_2 q}{1+b} \quad (8)$$

where β is the frequency reuse factor, and b accounts for the excess bandwidth required for practical filters and the guard-bands between FDMA channels. We used $b = 0.2$ as a typical implementable value.

The ACI term is a function of the frequency spacing between carriers, transmit symbol rate (i.e., modulation and coding dependent), transmit and receive filter characteristics, and frequency uncertainty. (E_b/I_{o-ACI}) values were calculated by assuming that the transmit and receive filters have a raised-cosine characteristic with a roll-off of 0.2. Note that since ACI is mainly due to differential frequency offset, it was considered only for the return link. A worst case differential frequency uncertainty of ±400 Hz was assumed for the return link.

The candidate modulation techniques considered for the digital FDMA were:

- coherent 16-state Trellis-Coded-8PSK (TC-8PSK),
- coherent 4PSK with rate 3/4 convolutional coding (constraint length of 6).

Both rate 3/4 coded 4PSK and TC-8PSK modulations were assumed to employ a short interleaver (with about 60 ms of total delay) to randomize most of the errors due to multipath.

The modem implementation loss was assumed to be 2 dB for 4PSK and 2.5 dB for TC-8PSK.

After AWGN, multipath and implementation loss are taken into account, the E_b/N_o' values required to obtain a BER of 10^{-3} are 7.3 dB for rate 3/4 coded 4PSK and 9.1 dB for TC-8PSK.

The maximum spectral efficiency of rate 3/4 coded 4PSK (including frequency reuse factor of 10/3) is 4.17 b/s/Hz, while TC-8PSK can achieve 5.56 b/s/Hz. Based on equation (5) and the above given E_b/N_o'values, it can be concluded that in the power limited region rate 3/4 coded 4PSK is more efficient. However, if sufficient power is available, TC-8PSK can achieve a better spectral efficiency.

3.3 ACSSB

In ACSSB, the mean opinion score (MOS) is used as a mechanism for quantifying subjective acceptability. C/N_o required per channel, $(C/N_o)_{ch}$, was obtained from experimental data [6,7] by determining the operating point from the channel parameters and the interference levels.

Considering a voice activity factor of 0.4 and a channel spacing of 5 kHz, the total C/N_oW_s can be expressed as

$$\frac{C}{N_oW_s} = 0.8 \times 10^{-4} \beta (\frac{C}{N_o})_{ch} \quad (9)$$

where $\beta = 10/3$ is the frequency reuse factor.

For a MOS of 2.5 and the multi-beam geometry of Fig. 1, the required $(C/N_o)_{ch}$ for the forward and return link are found as 47 dB-Hz and 48 dB-Hz respectively. These values include a margin of 1 dB for phase noise, amplifier nonlinearity and filtering.

Note that for the beam geometry assumed, ACSSB can readily achieve its bandwidth-limited capacity without utilizing dual polarization. Hence only single polarization has been considered.

4. Capacity Comparisons

In this section the forward and return link capacities of CDMA and FDMA schemes are compared. The C/N_oW_s values used in the comparisons are 10 dB and 20 dB. Table 1 presents the capacities for the 10 dB C/N_oW_s value which corresponds to a power limited condition for the candidate systems. Table 2 presents the capacities for the 20 dB C/N_oW_s value, at which the FDMA candidates have reached their bandwidth-limited capacities, and CDMA curves are approaching their asymptotes.

Note that an excess power margin (beyond the bandwidth-limited C/N_oW_s) does not increase capacity but increases the GOS to above 90%.

5. Capacity Enhancement

Some further potential capacity enhancement techniques which were not included in the analysis are briefly discussed below.

5.1 CDMA

For CDMA, using 4PSK rather than BPSK would distribute the self noise among orthogonal dimensions of the signal space. Thus 4PSK could increase the capacity by 60% and 90% at C/N_oW_s values of 10 dB and 20 dB respectively.

Bit or chip synchronization permits one to choose spreading codes which are approximately orthogonal, thus reducing the self noise.

As a consequence of above mentioned enhacements, the capacity of CDMA would significantly improve. However, this may be practical only in the forward link. Since the CDMA sys-

Table 1: **Capacity at C/N_oW_s= 10 dB.**

System	Capacity (b/s/Hz)
CDMA Forward Link	2.3
CDMA Return Link	4.1
Digital FDMA Forward Link	4.17[1]
Digital FDMA Return Link	3.7[1]
ACSSB Forward Link	2.4[2]
ACSSB Return Link	2.4[3]

1. 4PSK with rate 3/4 coding
2. 2 dB excess margin available
3. 1 dB excess margin available

Table 2: **Capacity at C/N_oW_s= 20 dB.**

System	Capacity (b/s/Hz)
CDMA Forward Link	3.1
CDMA Return Link	8.3
Digital FDMA Forward Link	5.56[1,2]
Digital FDMA Return Link	5.56[1,3]
ACSSB Forward Link	3.2[4]
ACSSB Return Link	3.2[5]

1. TC-C8PSK
2. 6.5 dB excess margin available
3. 5.2 dB excess margin available
4. 8.8 dB excess margin available
5. 7.8 dB excess margin available

tem has a lower relative capacity in the forward link, the associated complexity might be justifiable.

5.2 FDMA

Subdividing each beam into many sectors described by constant interference level boundaries and assigning location dependent frequency or polarization is expected to improve the capacity.

Capacity enhancement with ACSSB is limited to reducing spectral occupancy and channel spacing. A 20% increase (corresponding to a reduction in channel spacing from 5 kHz to 4 kHz) is achievable in the bandlimited region; resulting increased sensitivity to interference may be offset by resorting to dual polarization.

6. Conclusions

Based on the results presented above, the following conclusions can be drawn.

- For both FDMA systems, the disparity between the forward and return link capacities is negligible.
- The CDMA capacity for the forward and return links display a wide variance. In all cases the return link provides higher capacity.
- At low C/N_oW_s values (i.e., up to 10 dB) the capacity of digital and ACSSB FDMA are comparable. At higher C/N_oW_s values digital FDMA provides more capacity then its analog counterpart, while ACSSB FDMA has larger excess margins available (which yields better voice quality/higher GOS).
- In the forward link, digital FDMA provides more capacity than CDMA. The differential between digital FDMA and CDMA decreases with increasing GOS.
- In the return link, CDMA provides more capacity than digital FDMA. The differential between digital FDMA and CDMA remains fairly constant as GOS is increased.
- Both FDMA system capacities are sensitive to channelization, while CDMA is not.
- In [3] other beam contours have been considered. Capacity increases with increased coverage area, while the relative performance of the various schemes was the same as for the smaller coverage area.

It can be concluded that all systems considered possess various possibilities for enhancement, but the capacity improvements available to CDMA are probably larger and more easily attainable.

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